Task 1 Report – Literature Review

Feasibility of Nonproprietary Ultra-High Performance Concrete (UHPC) for Use in Highway Bridges in Montana: Implementation

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1 Introduction

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes costing approximately 30 times more than conventional concrete. Previous research conducted at Montana State University (MSU) has focused on the development and evaluation of nonproprietary UHPC mixes made with materials readily available in Montana. These mixes are significantly less expensive than commercially available UHPC mixes, thus opening the door for their use in construction projects in the state. The focus of the proposed project is on taking this material beyond the laboratory, and successfully using it on a bridge project in Montana, specifically for field cast joints. This project is a required step to fully understand and capitalize on the benefits of using UHPC for this application and increase the performance, durability, and efficiency of Montana bridges.

The specific tasks associated with this research are as follows:

Task 0 – Project Management

Task 1 – Literature Review

Task 2 – Close Minor Research Gaps

Task 3 – Bridge Construction and Related Activities

Task 4 – Monitoring Bridge Performance

Task 5 – Analysis of Results and Reporting

This report documents the work completed as part of Task 1 – Literature Review. This review includes recent research pertaining to the use of UHPC in actual bridge applications. It should be noted that the document will continue to be updated as research progresses.

2 Background

Previous research at MSU developed a nonproprietary mix design that has a 28-day compressive strength of 18 ksi, and is significantly less expensive than proprietary UHPC mixes [1, 2]. The focus of this project is on the field implementation of the MT-UHPC developed in this initial research. Specifically, the MT-UHPC was used in two bridges on Highway 43 near Lost-Trail Pass outside of Wisdom, MT. The MT-UHPC was used to connect precast pile caps to steel piles, and was used in longitudinal joints between precast/prestressed hollow-core bridge beams. The literature review will focus on aspects of UHPC research specifically related to the proposed application. In particular, it will focus on the use of UHPC in field-cast joints, and on nonproprietary formulations of UHPC.

3 FHWA Report on the Design and Construction of Field-Cast UHPC Connections

In 2014 the FHWA published a report with guidance on the design and field implementation of UHPC connections [3]. This report highlights techniques and considerations learned from previous research and previous applications of UHPC in the field. The following subsections highlight some of the key takeaways from this report.

3.1 Surface Preparation for Bond Between UHPC and Precast Concrete

Surface preparation of precast components is critical to ensure durability and long-term performance. UHPC can bond exceptionally well to conventional concrete if the surface is prepared properly. Lack of bond can affect the structural integrity of the connection and can allow water infiltration that may accelerate rebar deterioration. Successful bonding has been demonstrated between precast conventional concrete and UHPC if the surface of the precast element is roughened as shown in Figure 1. This can be created by applying a gelatinous retarder to the formwork. Additionally, it was found that pre-wetting the interface to an SSD condition improves bonding. This can be achieved by spraying the bonding surface with water while preventing too much water pooling in the forms. Additionally, wetting the surface will limit dehydrating effects between a dry surface and the freshly placed UHPC.

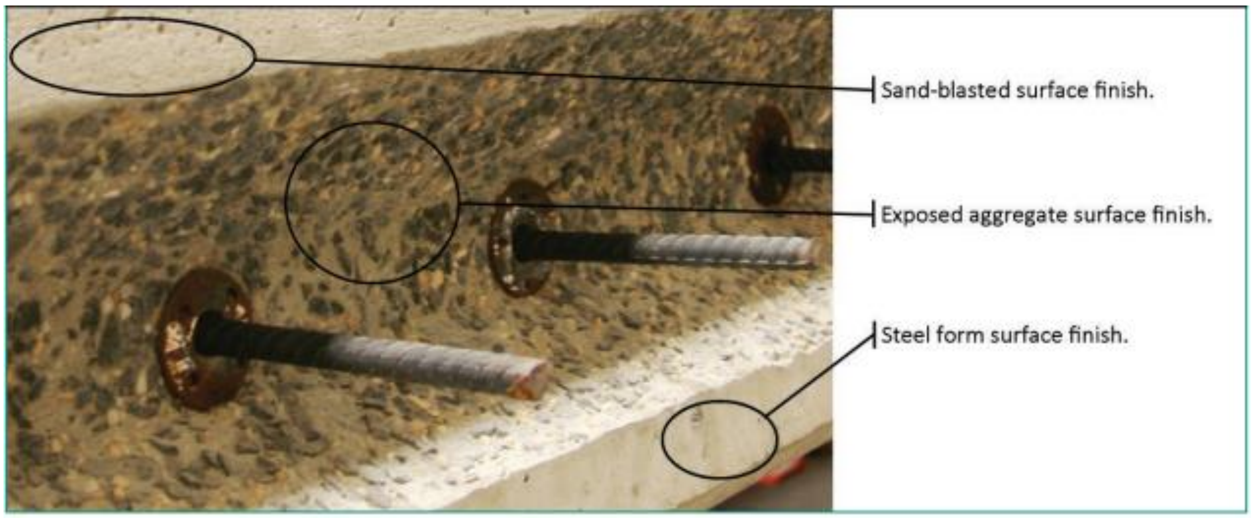

Figure 1: Exposed aggregate surface finish on a precast concrete component [3]

3.2 Formwork for UHPC Elements/Connections

UHPC is typically self-consolidating and more fluid than conventional concrete; therefore, the use of UHPC results in higher form pressure, which needs to be accounted for during formwork design. Additionally, the formwork needs to be fully sealed to ensure UHPC does not leak from the forms. To ensure a proper seal, contractors have checked seals with water prior to UHPC placement. A pathway for air must also be provided during placement to avoid entrapping air within the formwork. Similar to grout, UHPC should be placed starting at the low end of the pour and working towards the high end. Additionally, if the bridge has a slope, the formwork should be capped to prevent material from flowing over the joint at the low end, and intermittent holes should be included as a pathway for entrapped air to escape. Further, UHPC should be cast higher than the surface of the field cast joint so that it can be ground to remove the air bubbles near the surface of the UHPC.

3.3 UHPC Mixing Considerations

UHPC is sensitive to mixing conditions including temperature and the mixing process/procedure. Mixing UHPC involves an exothermic reaction, which can cause water loss due to evaporation, especially if mixing is takes place at elevated temperatures. Therefore, it is best to mix UHPC at cooler temperatures, somewhere between 50-60˚F, and out of direct sunlight and protected from wind. It has been found that fluidity is significantly reduced if the mix reaches a temperature of 80˚F, so mix temperature should be monitored. To reduce temperature effects, replacing water with cubed ice has been found to be effective.

The UHPC mixing process can strain the mixer being used. Specifically, after the mix water is added, the mix tends to stiffen up significantly prior to turning over, which can cause the mixer to bog down. Therefore, mixing UHPC requires high-capacity high-shear mixers that can handle the increased demands of mixing UHPC, or smaller batches must be used. As a target, the quantity of UHPC that can be mixed in is approximately half the volume that could be mixed with conventional concrete or grout. It is recommended that contractors perform trial mixes prior to the project to ensure proper batch sizes and mixing procedures.

3.4 Placing and Finishing UHPC

Traditionally, wheelbarrows or the like are used to transport the UHPC from mixer to the field joint (Figure 2). It is possible to pump or chute UHPC; however, these methods should be carefully coordinated in advance to ensure feasibility of transporting material to the connections. Traditional concrete finishing practices are not applicable to field-cast UHPC. Bleed water is virtually eliminated by the low water-to-cement ratio. Typically, the UHPC is placed in a closed form with the top form in contact with the material to minimize surface dehydration. If the surface will be visible to the public, the connection is frequently overfilled and ground to match the adjacent surfaces. Contractors have reported that grinding is easier if completed before the material reaches full strength. It is important that the UHPC doesn’t freeze before reaching a compressive strength of 10 ksi. Although cooler temperatures are ideal for mixing and placing, warmer temperatures increase the rate of strength gain. Supplemental heat sources can be used externally with ground heating mats or internally with resistance heating wires. However, heat sources that force heated air on the material should not be used on surfaces of freshly placed UHPC. Formwork is then finally stripped after a compressive strength of 14 ksi. This is also when traffic and live loads are allowed on the structure.

Figure 2: Longitudinal connections placed using a wheelbarrow [3]

4 Commercial Production of Nonproprietary Ultra-High Performance Concrete (Michigan)

Previous research at the University of Michigan focused on the development and characterization of nonproprietary UHPC mixes [4]. This research resulted in a viable nonproprietary UHPC mix; however, the use of this material in an actual field application was not successful. A follow-on study was performed to investigate why this recently developed mix did not successfully scale up to field implementation [5]. Based on the findings of this investigation, the mixing process was then adjusted accordingly and the UHPC mix was successfully used in a bridge application project [5]. This section summarizes the key findings from this investigation.

4.1 Reasons for Failed Field Implementation

The nonproprietary mix developed at the University of Michigan [4] performed exceptionally well in the laboratory, but it could not be successfully mixed during several field trials. Several factors contributed to this. It was determined that the silica fume used in the field had a high carbon content that drove up water demand, and the dosage rate of high range water reducer (HRWR) was too low to compensate for this higher water demand. Also, the silica fume used in the field trial was densified, which posed a challenge for the mixer to disperse during dry mixing. Finally, the field mixer did not have the capacity to induce turnover in the wet mix. Essentially, it was found that a proper dose of HRWR is key in successfully mixing UHPC.

4.2 Mixing Protocol:

Field mixing, in contrast to laboratory mixing, has some limitations. Large capacity mixers generally have lower mixing speeds than smaller lab mixers, which can lead to the formation of silica sand clumps that hinder mixing action. Further, as stated previously, mixing large UHPC batches can strain the mixer, and therefore mixes should be limited in size and be appropriate for the size of mixer being used. A procedure was developed to minimize these effects. Specifically, they found it beneficial to withhold half of the sand until after the mix water had been added and the mix had turned over.

4.3 Successful Field Implementation

UHPC was implemented on a bridge repair on the Pine River in Kenockee Townhill, MI. This repair entailed using UHPC to replace the joints connecting the reinforced concrete slabs. Mixing was achieved using two Mortarman 360 MBP pan mixers with capacity of 8 cu ft. However, each mix was limited to 5.5 cu ft. Once the mix turned over, the material was discharged into wheelbarrows to be transported to the pour location.

The mixing process took place on a hot day with forecast ranging from 73˚F to 89˚F. The first batch was mixed at an ambient temperature of 75˚F. The maximum mix temperature was 80˚F and the spread was 9.4 in. However, the second batch was mixed at 77˚F ambient temperature, and the mix temperature rose to 95˚F, resulting in a 7.4 in spread. To address this issue, cubed ice was added as a replacement for 40% of the water to keep the mix temperature below 85˚F. Mixes that rose above this temperature seemed to result in significant drop in spread.

The UHPC was cast at a rate slow enough to minimize flow lengths and the resultant preferential alignment of steel fibers. Specifically, the UHPC was placed at a speed comparable to the flow speed of the fresh mix.

Additionally, the forms and surface of concrete and rebar were pre-wetted to prevent the mix from losing water to dry surfaces. Once casting was finalized, top forms were added to reduce surface dehydration.

(a) Pre-wetting surfaces and placement of UHPC (b) Top forming after placement

Figure 3: Longitudinal joints during and after UHPC placement [5]

The formwork was stripped after one day and the top surface was observed to have small holes and shrinkage cracks. However, the underlying material was examined and was found to be in good shape. No grinding or overpouring was performed in this application.

5 First Application of UHPC Bridge Deck Overlay in North America

Researchers at Iowa State University evaluated the use of ultra-high-performance concrete (UHPC) as a bridge deck overlay [6]. This was the first time this was attempted in North America. The research was first focused on developing and characterizing a thixotropic UHPC mix design. Typical UHPC mixes have high flows and are not suitable for applications on slopes, and therefore a thixotropic mix is required for the proposed application. A UHPC mix suitable for applications on slopes of up to 7% was developed in cooperation with LafargeHolcim. The feasibility of this mix was then tested in the structural engineering laboratory at Iowa State University by placing the overlay mix on inclined slabs with varied surface preparations. The results from the laboratory investigation demonstrated the feasibility of its use in this application and were used to determine proper surface roughness and overlay thickness.

After the initial phases of this research, the thixotropic UHPC mix design was used as an overlay on the Mud Creek Bridge on Buchanan County Road D48 near Brandon, Iowa. This bridge is 102 ft long and 30 ft wide, and is a continuous concrete slab bridge with two lanes. For this project, the top 0.25 in of the deck surface was first removed, and the deck was then grooved along the bridge length with an amplitude of roughness ranging from 1/12 in to 1/8 in. All batching and placing of the UHPC was performed on site by the contractor. A pair of high-shear pan mixers were used to mix the concrete. Each mixer had the capacity to mix 0.65 yd^3 (17.55 ft^3) of material. Loading and batching of the UHPC took approximately 20 minutes per batch. An overlay thickness of 1.5 in was compacted and maintained by using a vibratory truss screed. All the mixing was done at one end of the bridge and transported using a mini concrete dumper. Grinding and grooving of the UHPC deck surface took place 4 days after placement (Figure 4), at which point the compressive strength had reached 12.3 ksi. Finally, the deck was evaluated using pull-off tests to quantify the bond strength between the UHPC and the substrate material.

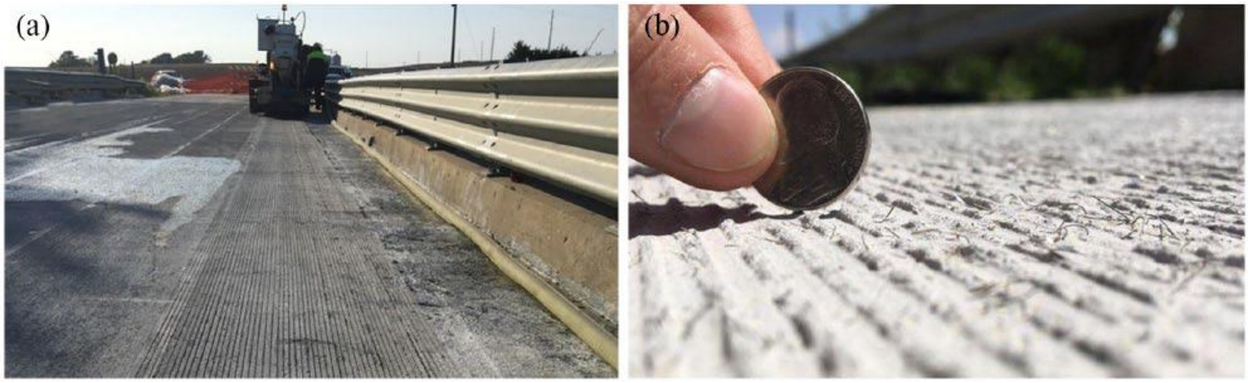

Figure 4: UHPC overlay on Mud Creek Bridge deck: (a) grooving of the surface; (b) closeup of finished surface [6]

This project was deemed successful, and the experience revealed areas for improvement on future UHPC projects. Batching the material with two mixers was satisfactory, but a sufficiently large, trained crew is also necessary. The consistency of the thixotropic UHPC mix was such that placing was difficult using racks and shovels. The crew needed for placing and screeding the overlay was about twice that required for a normal overlay. It was also found that lightly misting the UHPC in front of the vibrating screed helped consolidation and sticking issues. Additionally, the use of a curing compound was recommended to keep the moisture within the UHPC layer immediately after consolidation. It was determined that for this project, the total cost of the UHPC overlay was approximately $45/ft^2, including batching, placing, and grinding of the deck surface.

6 Utilization of Ultra-High Performance Concrete (UHPC) in New York

The New York State Department of Transportation's (NYSPDOT) has used UHPC in 30 construction projects involving prefabricated bridge elements with field-cast UHPC joints [7]. An example of one such project is shown in Figure 5. This section briefly reviews some of the key findings from this experience.

- First, overall, they found precast construction with UHPC joints to be an economical solution when accelerated construction is needed.
- The nonproprietary performance-based UHPC specification has performed well for NYSDOT.
- In terms of construction, in order to improve bonding of UHPC they recommend providing an exposed aggregate finish on the mating surface of the precast component.
- Additionally, they determined that it is critical to prewet the precast surfaces before filling the joints.
- They recommend overfilling the joints by at least ¼ in to deal with consolidation settlement of the UHPC.
- All formwork should be leak proof to ensure that the highly flowable UHPC does not leak out of the forms.
- The use of maturity meters are recommended to determine strength when accelerated curing is required.

- It was found that the contractor often didn't provide sufficient labor for the project, which led to some inefficiency. With more experience, DOT staff was able to guide contractors in later projects with compressed schedules to provide sufficient labor.
- Sufficiently large UHPC mixers are recommended to speed construction.
- Overall all bridges using precast elements with UHPC joints are performing well.

Figure 5: Example precast UHPC project in progress

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